Electron-Phonon Coupling in HTSCs

Strong Lattice Vibration Role in Superconductivity Suggested

The mechanism responsible for high-temperature superconductivity remains elusive. The observation of spectral features occurring at a characteristic energy (an energy scale) often provides significant insight into physical processes in the material. Now, an international collaboration between researchers from Stanford University, the University of Tokyo, and the Advanced Light Source (ALS) has evidence from high-resolution angle-resolved photoemission spectroscopy (ARPES) for a common energy scale in three different families of high-temperature superconductors. Several chains of evidence argue that, in contrast to most recent thinking, lattice vibrations must have a role in the superconductivity in these materials.

ARPES measures the photoemission intensity as a function of two variables, the electron binding energy (obtained from the photoelectron kinetic energy) and electron momentum (obtained from the angle of emission from the sample surface). With its ability to directly reveal energy–momentum relationships (dispersion curves) and lifetimes, ARPES provides a unique opportunity to look for energy scales that manifest themselves in dynamical parameters, such as the velocity (slope of energy-momentum curve) and scattering rate. The angular resolution of ±0.1 degrees, which is about an order of magnitude better than in many previous ARPES studies of these materials, made the new results possible.

The experimenters recorded their spectra at ALS Beamline 10.0.1 (some data were also taken at Stanford Synchrotron Radiation Laboratory Beamline 5.4) at several temperatures and photon energies on single crystals of $Bi_2Sr_2CaCu_2O_8$ (Bi2212), lead-doped $Bi_2Sr_2CaCu_2O_8$ (Pb-Bi2212), lead-doped $Bi_2Sr_2CuO_6$ (Pb-Bi2201), and $La_{2-x}Sr_xCuO_4$ (LSCO). These representative high-temperature superconductors exhibited a range of transition temperatures and energy gap values.

A typical momentum distribution curve (MDC), obtained by plotting the photoemission intensity as a function of scanning angle at a constant binding energy, shows a peak on a constant background that can be fitted to obtain one point on an energy–momentum curve. The dispersion curves derived from many MDCs for each material clearly showed the energy moving linearly towards the Fermi energy (binding energy = 0) as the momentum decreased. Most important, however, the curves exhibited an obvious kink in the slope near a binding energy of 50–80 meV, independent of the material's superconducting transition temperature and energy gap.

The change in slope to a lower value close to the Fermi energy suggests the onset of a many-body effect involving electrons and some other entity to form a heavier, slower quasiparticle. Universality of the kink in the various materials and its uniformity for different directions of momentum in the Brillouin zone lead naturally to the conclusion that a very strong electron–phonon coupling is responsible. Persistence of the kink above the transition temperature further supports this conclusion because phonons would be active over a wide temperature range. Neutron-scattering experiments by another group on $La_{2-x}Sr_xCuO_4$ show that the energy of an oxygen stretching vibration (longitudinal optical phonon) matches that of the kink, suggesting this phonon mode as involved.

Additional evidence comes from energy distribution curves (EDCs), obtained from the photoemission intensity variation with binding energy at a fixed angle for several $Bi_2Sr_2CaCu_2O_8$ samples with different transition temperatures. The set of EDCs for each material exhibited a common structure showing a quasiparticle peak at energies close to the Fermi energy, a dip occurring approximately at the phonon energy, and a broad feature at higher energy. Similar EDCs are observed for the beryllium surface, whose electrons are known to have a strong coupling to a single phonon mode, and to simulated EDC spectra for the simple case of isotropic coupling to a single phonon mode.

These findings and others obtained from additional detailed analysis of the ARPES data, bring the electron–phonon interaction back as an important player in the high-temperature superconductivity puzzle. ■

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A. Lanzara, P.V. Bogdanov, X.J. Zhou, S.A. Kellar, D.L. Feng, E.D. Lu,T. Yoshida,H. Eisaki, A. Fujimori, K. Kishio, J.I. Shimoyama, T.Noda, S. Uchida, Z. Hussain, and Z.X. Shen, "Evidence for Ubiquitous Strong Electron–Phonon Coupling in High-Temperature Supereconductors," *Nature* **412**, 510 (2001).

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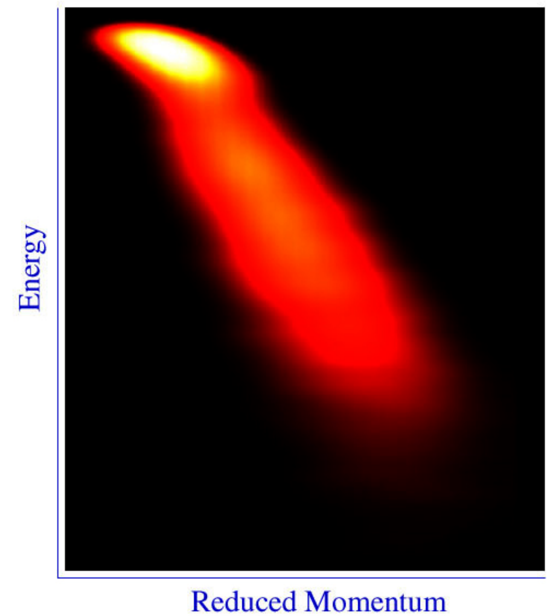
- **Mechanism of high-temperature superconductors (HTSCs) unexplained**
  - *Electron-phonon interaction underlines conventional superconductors*
  - *Previous experiment and theory suggest a different mechanism is operative in HTSCs*

PHOTOEMISSON INTENSITY



- **Angle-resolved photoemission (ARPES)**
  - *High angular resolution at the ALS probes electron dynamical parameters*
  - *Feature at characteristic energies give insight into operative physical processes*
- **New APRES evidence from three familes of HTSCs**
  - *Kink in electron-momentum (dispersion) cureves ubiquitous in all three*
  - *Common kink energy and other evidence suggests electron-phonon coupling*
  - *Revives question of role of phonons in driving superconductivity in HTSCs*

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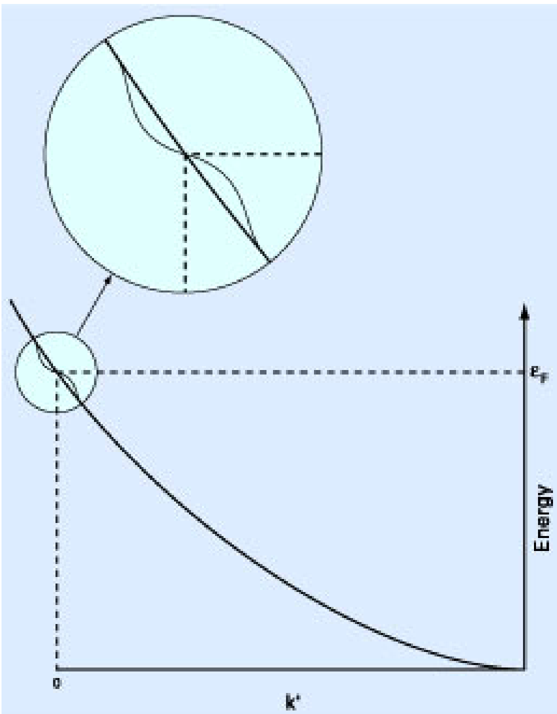

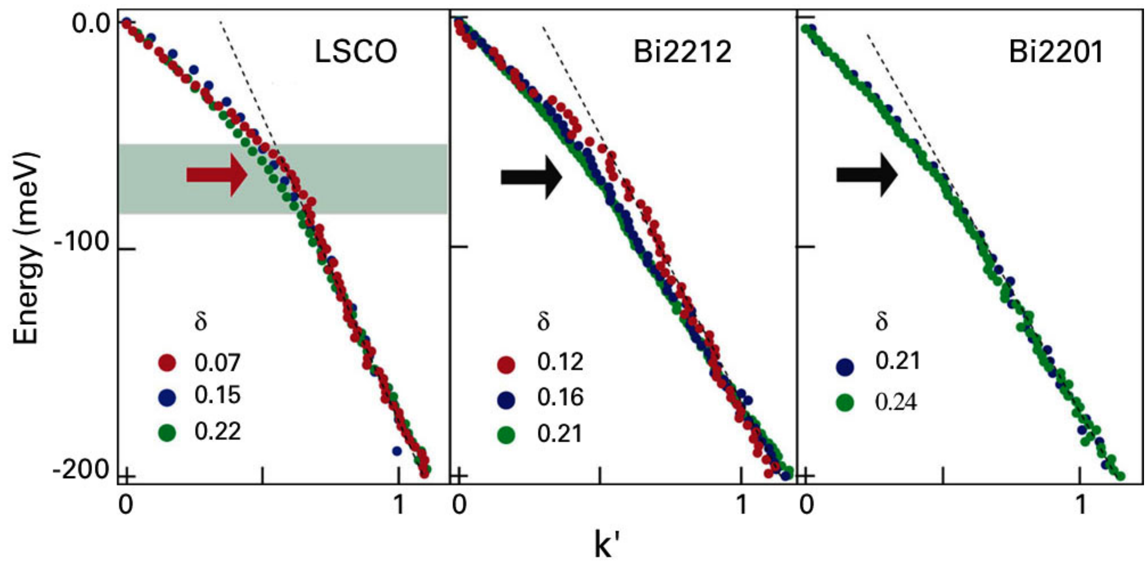

(left) Electro-phonon coupling modifies the electron-momentum dispersion curve near the Fermi energy. (right) Dispersion curves for three families of high-temperature superconductors show a common kink at an energy (arrow) that matches an oxygen lattice vibration. The parameter δ is the doping concentration that determines the transition temperatures in the materials. k' is the reduced momentum (momentum at the Fermi energy k_f minus the actual momentum k).

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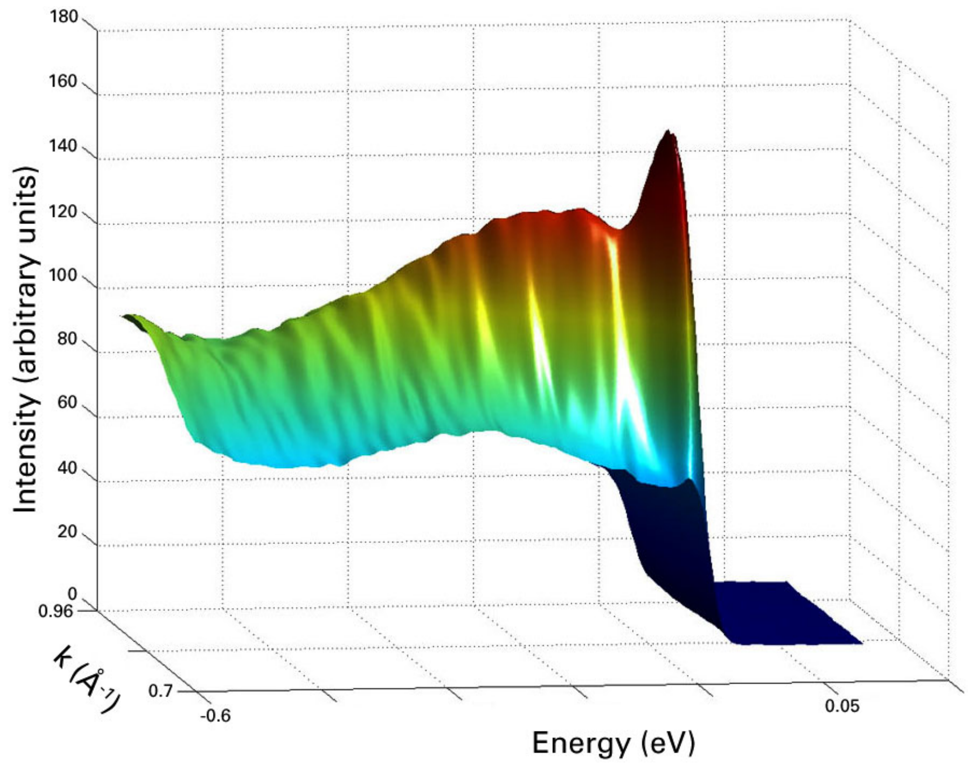

Set of photoemission energy distribution curves (EDCs)at different angles (colors) for a HTSC. Similar sets measured for three families of HTSCs and the non-superconducting beryllium surface and simulated for the simple case of isotropic coupling to a single phonon mode share common features, suggesting electron-phonon coupling is operative in HTSCs

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